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Growth overfishing in the brown shrimp fishery of Texas, Louisiana, and adjoining Gulf of Mexico EEZ

C.W. Caillouet Jr. [a], R.A. Hart [b,*], J.M. Nance [b]

[a] 119 Victoria Drive West, Montgomery, TX 77356, USA
[b] National Marine Fisheries Service, Galveston Laboratory, 4700 Avenue U, Galveston, TX 77551 USA

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Abstract

Growth overfishing in the brown shrimp, *Farfantepenaeus aztecus*, fishery in inshore (estuarine) and offshore (Gulf of Mexico) territorial waters of Texas and Louisiana, and adjoining waters of the United States' (U.S.) Exclusive Economic Zone (EEZ), and its potentially detrimental economic consequences to the harvesting sector, have not been among major concerns of Federal and State shrimp management agencies. Three possible reasons include (1) environmentally influenced variations in recruitment that cause wide fluctuations in annual landings, which tend to obscure effects of fishing, (2) competition between inshore and offshore components of the harvesting sector, and (3) partitioning of management jurisdiction among a Federal council and two State agencies. Wide variations in landings led to beliefs that high levels of fishing mortality were tolerable and recruitment overfishing was of no major concern. This encouraged somewhat *laissez-faire* management approaches that allowed fishing effort to increase over the years.

Our objectives were to determine whether growth overfishing occurred in this fishery during 1960–2006, and whether and how decreases in size of shrimp within the landings, in response to increases in fishing effort, affected inflation-adjusted annual (calendar year) ex-vessel value of the landings, i.e., their value to the harvesting sector. Growth overfishing occurred in the early 1990s, and then abated as fishing effort declined due to rising fuel costs and competition from imported shrimp. However, inflation-adjusted annual ex-vessel value of the landings peaked in 1985, prior to growth overfishing.

Management actions implemented in 2001 for Texas' territorial waters, and in the EEZ off Texas and Louisiana in 2006, should limit future fleet expansion and increases in fishing effort, thereby reducing the chances of growth overfishing and its potentially detrimental economic impacts on the harvesting sector. Growth overfishing should be included among the guidelines for future management of this brown shrimp fishery.
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Keywords: Brown shrimp fishery; Growth overfishing; Gulf of Mexico; Texas; Louisiana; Exclusive Economic Zone

1. Introduction

The brown shrimp, *Farfantepenaeus aztecus*, fishery in Texas and Louisiana, and adjoining waters of the United States' (U.S.) Exclusive Economic Zone (EEZ) in the Gulf of Mexico produced 86% of the combined annual landings of brown shrimp from EEZ and State waters of the northern Gulf of Mexico in 2006. In that year, annual landings of brown shrimp from this fishery totaled 33.7 thousand metric tonnes (74.4 million pounds avoirdupois), valued at 148.8 million U.S.$ to the fishers (harvesting sector). Our use of the term "landings" herein refers to brown shrimp caught within the boundaries of this fishery and landed. Harvest takes place within Shrimp Statistical Subareas 13–21 (Fig. 1), encompassing inshore (estuarine) and offshore (Gulf of Mexico) State territorial waters of Texas and Louisiana, and a part of the adjoining Federal EEZ. Accordingly, management jurisdiction for this fishery is partitioned among two State agencies, Texas Parks and Wildlife Department (TPWD) and Louisiana Department of Wildlife and Fisheries (LDWF), and a Federal (U.S.) council, the Gulf of Mexico Fishery Management Council (GMFMC).[1]

* Corresponding author. Tel.: +1 409 766 3404; fax: +1 409 766 3508.
E-mail address: rick.hart@noaa.gov (R.A. Hart).

[1] Shrimp fishery management plans include (1) the Fishery Management Plan for the Shrimp Fishery of the Gulf of Mexico, United States Waters, Gulf of Mexico Fishery Management Council, Tampa, FL, November 1981 (http://www.gulfcouncil.org), (2) the Texas Shrimp Fishery, a report to the Governor and the 77th Legislature of Texas, Executive Summary and Appendices A–H, September 2002 (http://www.tpwd.state.tx.us/publications/

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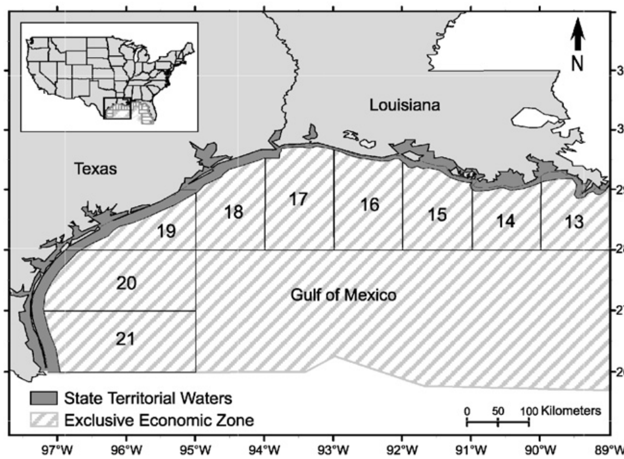

Fig. 1. Shrimp Statistical Subareas 13–21, encompassing the brown shrimp fishery in inshore (estuarine) and offshore territorial waters of Texas and Louisiana, and adjoining waters of the Exclusive Economic Zone (EEZ) in the Gulf of Mexico.

Historically, the possibility of growth overfishing and its potentially detrimental economic consequences to the harvesting sector have not been major concerns of Federal and State fishery management agencies. Growth overfishing occurs when fishing effort is higher and size of harvested individuals is smaller than levels of effort and size that produce maximum sustainable yield (MSY) or maximum yield-per-recruit in a fishery. Ex-vessel value is the amount of money paid to the harvesting sector for brown shrimp harvested within this fishery and landed. Kutkuhn (1962) showed that ex-vessel value per unit weight of shrimp increases with an increase in the size of shrimp. Therefore, the decrease in size of shrimp that accompanies increasing fishing effort, combined with a decline in landings of shrimp, can decrease ex-vessel value of the annual landings (Caillouet and Patella, 1978; Caillouet et al., 1979, 1980a,b; Caillouet and Koi, 1980, 1981a,b, 1983). The competition from imported shrimp exacerbated this problem, by reducing the domestic price per pound of shrimp (Keithly and Roberts, 2000).

Neal and Maris (1985) recognized that growth overfishing of shrimp stocks (multiple species) in the Gulf of Mexico could produce significant economic problems. Condrey and Fuller (1992) remarked that the northern Gulf shrimp fishery is “a classic example of an open access fishery which has been allowed and, in some cases, encouraged to expand well beyond the point of maximum net economic return”. A very important aspect of growth overfishing is that it does not affect the ability of a population to replace itself (Gulland, 1974). However, more than two decades ago, Rothschild and Brunenmeister (1984) warned that an increase in fishing effort in the northern Gulf shrimp fishery could result in increased risk of population collapse or a sustained reduction in production of the population. Yet, fishing effort was allowed to increase until exogenous factors, including rising fuel costs, competition from imported shrimp, and damage to the fleet by recent hurricanes, contributed to its decline.[2]

Neal and Maris (1985) thoroughly reviewed the brown shrimp’s life cycle and fishery characteristics. Brown shrimp are short-lived, have high fecundity, have the potential to spawn more than once within a year, and produce annual crops. Individual brown shrimp can live slightly more than 2 years, but high natural and fishing mortality reduce the life span of most brown shrimp in the fishery. Females mature and spawn in the Gulf of Mexico, where eggs hatch and larval development occurs. Brown shrimp enter coastal estuaries as postlarvae and grow to juvenile and subadult stages before emigrating offshore to mature and reproduce. Harvest of each new annual crop begins with juveniles and subadults inshore, and then continues offshore through the adult life stage. Wide variations in year-class strength are more influenced by environmental factors affecting survival and distribution of the early life stages than from the number of eggs spawned. These environmental factors lead to variations in recruitment that cause wide variations in annual landings.

One possible reason that Federal and State fishery management agencies have seemed relatively unconcerned about the possibility of growth overfishing in this fishery may have been that environmentally influenced fluctuations in annual landings obscured the effects of fishing, making growth overfishing difficult to detect. Another possible reason could be that different brown shrimp life stages are harvested inshore and offshore by different harvesting sector components that compete for shares of the annual crop. A third possible reason is that fishery management jurisdiction is spread among three independent management entities (TPWD, LDWF, and GMFMC) which use different management strategies. Recognition that wide variations in annual landings were largely the result of environmentally influenced variations in recruitment also led to beliefs that high levels of fishing mortality were tolerable and recruitment overfishing was of no major concern (Neal and Maris, 1985). These beliefs in turn encouraged somewhat *laissez-faire* fishery management approaches that allowed fishing effort to increase over the years.

The “conventional wisdom” that brown shrimp stocks can withstand increasingly high levels of fishing effort without substantial biological or economic risk is reflected in State and Federal fishery management plans (FMPs). The GMFMC’s shrimp FMP,[1] initiated in 1981, covers multi-species shrimp fisheries within the entire northern Gulf of Mexico EEZ. This plan defined MSY and optimum yield (OY) as “all the shrimp that can be taken during open seasons in permissible areas in a given fishing year with existing gear and technology without resulting in recruitment overfishing”. Although this plan has been amended 13 times, these definitions of MSY and

pwdpubs/media/pwd_rp_v3400_857.pdf), and (3) a Fisheries Management Plan for Louisiana’s Penaeid Shrimp Fishery, Louisiana Department of Wildlife and Fisheries, Baton Rouge, Louisiana, December 1992.

[2] Report to Congress on the Impacts of Hurricanes Katrina, Rita, and Wilma on Alabama, Louisiana, Florida, Mississippi, and Texas Fisheries, July 2007, U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Silver Spring, MD (http://www.nmfs.noaa.gov/msa2007/docs/HurricaneImpactsHabitat_080707_1200.pdf).

OY remain in effect. Based on recruitment overfishing thresholds established by the GMFMC as management criteria, there are "no Gulf of Mexico shrimp stocks subject to [recruitment] overfishing, no [recruitment] overfished stocks, and no stocks approaching a [recruitment] overfished condition". The 2006 report[3] on status of U.S. fisheries also indicated that Gulf of Mexico brown shrimp are not recruitment overfished. This focus on recruitment overfishing thresholds emphasizes the seeming lack of concern for the possibility of growth overfishing. TPWD's management authority over shrimp (multiple species) in Texas waters was initiated in 1989, the year in which Texas' shrimp FMP[1] was developed and adopted. Implemented in 1995 were a license limited entry program in the inshore shrimp fishery of Texas and a voluntary license buyback program, to reduce overcapitalization. LDWF published Louisiana's shrimp (multiple species) FMP[1] in 1992. All three FMPs employ a variety of management approaches that take advantage of annually varying shrimp crops. Until the 2000s, the focus of management was on controlling size and characteristics of shrimping vessels, boats, and gear, and on temporal–spatial closures to shrimping, which allowed small shrimp to grow to larger, more valuable sizes before harvest. An important example is the Texas Closure, implemented in 1981 as a Federal-State cooperative seasonal closure to shrimping in Texas' offshore waters and the EEZ off Texas (Klima et al., 1982; Nance et al., 1994).

After Nance et al. (1989) observed that Gulf of Mexico brown shrimp stocks were growth overfished, Onal et al. (1991) concluded that the Texas shrimp fishery could benefit from reduced fishing effort because of the accompanying improvement in size composition of the harvested shrimp. Nance et al. (1994) simulated effects of hypothetical temporal–spatial closures of Federal and State waters to shrimping for brown shrimp, and concluded that such closures could increase net profits to the harvesting sector if implemented. In 2000, the TPWD[4] determined that shrimp stocks in Texas bays were growth overfished, and in 2001 imposed additional regulations aimed at reducing size of the inshore fleet, reducing growth overfishing, and avoiding recruitment overfishing. Yet, Haby et al. (2002) predicted that impacts of these additional regulations on yield and ex-vessel value would be relatively minor across the shrimping industry in Texas. In April 2005, the GMFMC[5,6] acknowledged that the U.S. shrimping industry in the northern Gulf of Mexico EEZ was experiencing serious economic problems, attributing them to increased fuel costs and competition from imported shrimp (Keithly and Roberts, 2000). According to a July 2007 report to the U.S. Congress,[2] hurricanes Katrina (August 2005), Rita (September 2005), and Wilma (October 2005) accelerated the regional decline in shrimp fishery participation and production which began in 2001. This regional decline was influenced by high fuel costs, poor market prices for domestic shrimp, fishery overcapitalization, rising insurance costs, and the erosion and conversion of waterfront property in some areas from fishing industry use to tourism-based and alternative uses.[2] In addition, while these hurricanes caused substantial damage and loss to the harvesting and processing sectors of the shrimp industry, thereby further reducing fleet size and fishing effort, they apparently had no detrimental impacts on Gulf shrimp stocks. Finally, a temporary moratorium on fleet size in the EEZ, proposed in 2005 by the GMFMC,[5,6] was approved by the U.S. Secretary of Commerce in September 2006.

2. Materials and methods

In this paper, we revisit the topic of growth overfishing in this brown shrimp fishery, using a longer time series (calendar years T, 1960–2006) of fishery-dependent data than was available to previous investigators (Table 1). Our objectives were to determine whether growth overfishing occurred in this fishery, and whether and how decreases in size of shrimp within the landings, in response to increases in fishing effort, affected annual yield in weight, W, and annual inflation-adjusted ex-vessel value, V (Table 1). To accomplish these objectives, we fitted polynomial regressions (first through sixth order) to the time series of each fishery-dependent variable and to relationships between selected pairs of these variables, using analysis of variance (ANOVA; Sokal and Rohlf, 2000) to select which if any regressions were best fitting. The fishery-dependent variables were developed by summarizing data recorded by shrimping trip and archived by the National Marine Fisheries Service's (NMFS) laboratory in Galveston, TX.[7,8] Such annual summations aggregated the within-year changes in numbers and sizes of shrimp caused by recruitment, mortality, and growth. When we detected a significant trend or relationship, we examined it for significant linearity and curvilinearity. When significant curvilinearity occurred, we examined the curve for local maxima and minima. We also calculated an adjusted r^2, ANOVA F, and associated p (probability) as measures of goodness of fit for each best fitting regression.

Among the fishery-dependent variables chosen for our analyses (Table 1) were an annual index that represents the distribution of weight of landings among shrimp size groups, and another annual index that represents the distribution of nominal ex-vessel value of landings among shrimp size groups. These two indices provided novel ways of examining changes in size of brown shrimp in the landings, and their influences on annual yield and its inflation-adjusted ex-vessel value. They have not been

[3] NOAA's NMFS Report on the Status of the U.S. Fisheries for 2006 (http://www.nmfs.noaa.gov/sfa/domes_fish/StatusoFisheries/2006/2006RTC-Final_Report.pdf).

[4] Texas Shrimp Fishery Briefing Book April 2000, Texas Parks and Wildlife Department, Austin, TX.

[5] Final Draft Amendment Number 13 to the Fishery Management Plan for the Shrimp Fishery of the Gulf of Mexico, U.S. Waters with Environmental Assessment Regulatory Impact Review, and Regulatory Flexibility Act Analysis. April 2005, Gulf of Mexico Fishery Management Council, Tampa, FL, and National Marine Fisheries Service, Southeast Regional Office, St. Petersburg, FL.

[6] Minutes of the Gulf of Mexico Fishery Management Council 200th Meeting, Palace Hotel, Biloxi, Mississippi, May 11–12, 2005, Gulf of Mexico Fishery Management Council, Tampa, FL.

[7] See Nichols (1984).

[8] See Poffenberger (1991).

Table 1
Descriptions, symbols, and units of measure for annual (calendar year, *T*) fishery-dependent variables in the brown shrimp fishery of Texas, Louisiana, and adjoining Gulf of Mexico EEZ, 1960–2006

Variable	Symbol	Units of measure
Index of distribution of weight of landings among count categories	*b*	
Index of distribution of nominal ex-vessel value of landings among count categories	*d*	
Difference ($b-d$) between indices *b* and *d*	*D*	
Yield in weight of landings	*W*	Pounds (avoirdupois), heads-off
Nominal fishing effort	*E*	24-h days fished
Average weight of landings per unit effort	WPUE	Pounds (avoirdupois), heads-off
Yield in inflation-adjusted ex-vessel value of landings	*V*	U.S.$ (2006), heads-off
Average inflation-adjusted ex-vessel value per pound	VPP	U.S.$ (2006), heads-off

widely used in shrimp fishery assessments, but they are consistent with the theory underlying surplus production and provide useful additional information on the effects of fishing.

Shrimp harvesters and onshore shrimp processors size-grade shrimp with shells on, either whole (i.e., with heads on) or headed (i.e., heads-off, or "tails", the edible abdominal portion).[7,8] All weights of shrimp in this paper are heads-off weights (i.e., any that were originally reported as heads-on were converted to heads-off), and expressed in pounds avoirdupois (1 pound avoirdupois = 0.4536 kg). Most shrimp landings are graded into size class intervals expressed in count, which is the number of shrimp per pound (i.e., the reciprocal of weight per shrimp). In this paper, count is based on heads-off weight; in other words, the number of shrimp "tails" per pound.

2.1. Annual index b of the distribution of weight of landings among count categories

Annual size-frequency distributions of brown shrimp in the landings are unknown. However, the size-graded trip landings, allocated to count class intervals referred to as count categories, provide a useful alternative for examining changes in sizes of shrimp in the landings from year-to-year. In the absence of annual size-frequency distributions, Caillouet et al. (1980a,b) were the first to develop an annual index of the distribution of weight of landings among count categories, which they used to detect trends of decreasing size of brown shrimp in annual landings from Texas and Louisiana during 1959–1976. Thereafter, Caillouet and Koi (1980, 1981a,b, 1983) used this index, or modifications thereof, to detect trends of decreasing size of brown shrimp in annual landings from the Gulf and Atlantic coasts of the U.S., and to show how decreasing size affected their ex-vessel value.

Count categories used by shrimp harvesters and processors to report trip landings are numerous and widely variable, because they are related to marketing of shrimp of various sizes (Kutkuhn, 1962). However, eight standard count categories have been used for decades in shrimp stock assessments[1]; they are: <15, 15–20, 21–25, 26–30, 31–40, 41–50, 51–67, and >67 count. Two additional non-numerical categories are "pieces" (broken tails) and "unknown" (landings recorded without count class intervals). We assumed that annual landings in the "pieces" and "unknown" categories reflected the same proportionate distribution as that of size-graded annual landings apportioned among the eight standard categories. While this assumption cannot be tested, annual count-graded landings made up 97.5–100.0% of the annual yield (*W*) over all years, and therefore should well represent the annual distribution of weight of landings among count categories.

We allocated and summarized size-graded landings from all trips in each year into the eight standard count categories, using as count class markers the lower limits of the reported (recorded) count categories. The lower limit of a count category represents the largest shrimp possible within that count category. When the lower count limit of a count-graded portion of a trip's landings fell into one of the eight standard categories, we assigned the entire weight of that portion of the trip's landings to that standard category, even when the upper count limit fell outside the category. For example, if the landings from an individual trip were graded into two portions with count intervals of 18–26 and 27–50, these portions were assigned to the 15–20 and 26–30 standard count categories, respectively. Reasons for use of this allocation procedure will become evident in the description of the model used to estimate *b*, as elaborated below.Several important considerations influenced our decision to use lower limits as class markers for allocating trip landings to the eight standard categories instead of using midpoints or upper limits as class markers. First, class intervals of the standard count categories are not equal in width[7,8] (Kutkuhn, 1962). Second, the lower limit of the <15 count category is zero. Third, the >67 count category is open-ended, unless an upper bound is arbitrarily designated. Neither zero nor an open-ended upper limit of the >67 count category can be converted to weight per shrimp. In some cases, previous investigators[7] have chosen a non-zero lower limit for the <15 count category and designated an upper limit for the >67 count category, to allow their conversion to weight per shrimp, but we preferred not to do so because such choices are subjective.

The count-apportioned landings from all trips within a year were summed by count category to obtain annual pounds landed by count category, for each year 1960–2006. These sums were then cumulated by count category, starting with the category containing the smallest shrimp (>67 count) and continuing through the category containing the largest shrimp (<15 count), to obtain annual cumulative weight landed by count category. This accumulation is one of the main reasons that lower limits of count categories were used as class markers. Annual cumulative weight landed by count category was then converted to annual cumulative percentage of weight landed by count category. Because count is the reciprocal of weight per shrimp, annual cumulative percentage of weight landed by count category (on the ordinate) declines from its maximum of 100% to the left, when count is zero, to its minimum to the right.

The exponential model underlying estimation of b is

$$P_i' = a\,\mathrm{e}^{bC_i} \qquad (1)$$

where b is the annual index of the distribution of weight of landings among count categories; P_i' is the annual cumulative percentage of pounds landed within the standard count category with ith lower limit; C_i is the ith lower limit (15, 21, 26, 31, 41, 51, and 68) of seven ($i = 1, 2, \ldots, 7$) of the eight standard count categories, respectively; a is an empirical constant, and e is the natural logarithm base.

A natural logarithmic transformation of Eq. (1) linearized it to

$$\ln(P_i') = \ln(a) + bC_i \qquad (2)$$

Slope b of Eq. (2) was estimated by linear regression. Landings in the <15 count category were not included in this linear regression (Eq. (2)) to estimate b, because the percentage (by weight) of graded shrimp made up of shrimp in the <15 count category was disproportionately low over all years (0.6–5.7%). Therefore, the data point for the <15 count category ($P_0' = 100$, where $i = 0$) did not follow the linear regression (Eq. (2)) based on the other seven count categories. Examples of cumulative percentages P_i' and the linear regression (Eq. (2)) are shown in Fig. 2A and B, respectively, for year 1981 that had the highest W. A right facing tick mark on the ordinate of Fig. 2B marks the data point for the <15 count category, which was included in the graph only for visual comparison with data points of the other count categories.

Because annual index b has only negative values (Eq. (2); Table 2; Fig. 2B), an increase in b indicates a decrease in size of shrimp in the landings, and a decrease in b indicates an increase in size of shrimp in the landings. Although this may cause some confusion, it should be more understandable when one considers how the use of count (the reciprocal of weight per shrimp) as a measure of shrimp size in the landings affects perception of index b. For purposes of our analyses, we believe that b substantially represents the annual distribution of weight of landings among the count categories, because it is based on 92.6–98.8% of W. These high percentages exclude landings in the <15 count, "pieces", and "unknown" categories. It is clear that index b is a useful single statistic for examining trends in distribution of weight of landings among count categories, as well as relationships between b and other fishery-dependent variables. The empirical constant, $\ln(a)$, also estimated in fitting

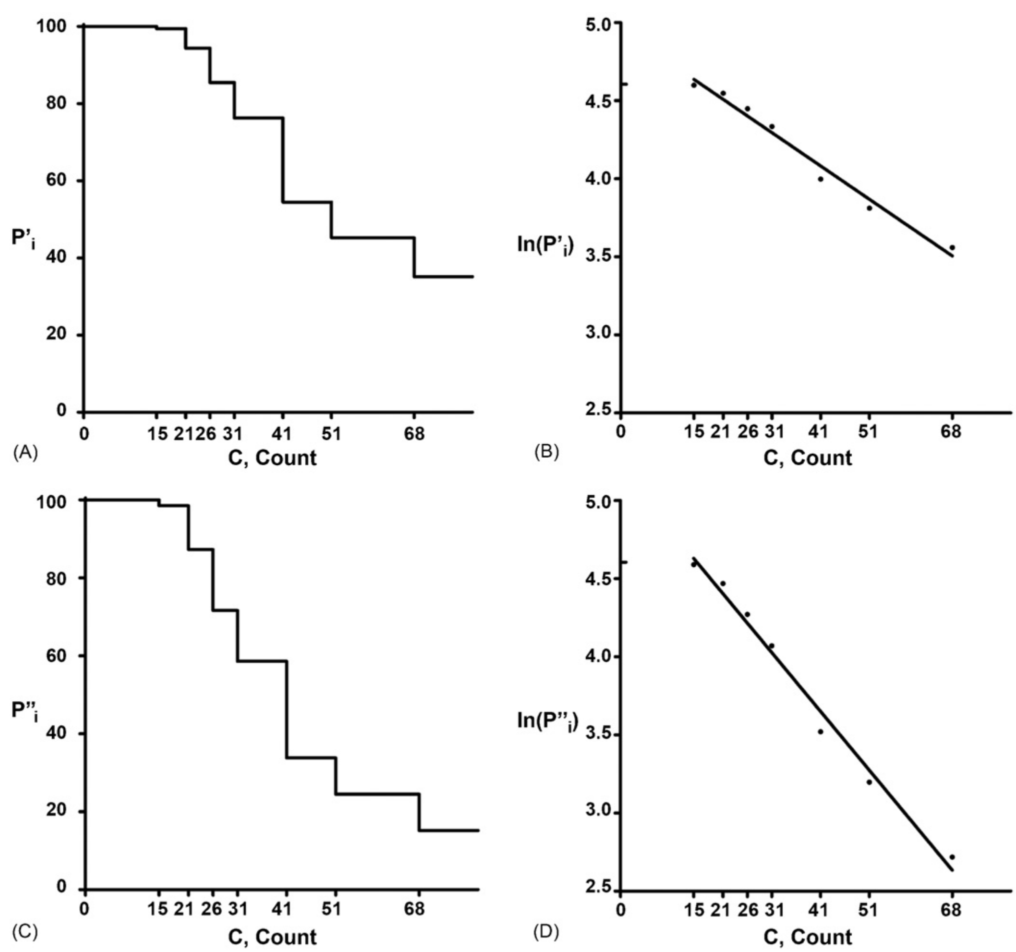

Fig. 2. Example relationships between P_i' and C_i, $\ln(P_i')$ and C_i, P_i'' and C_i, and $\ln(P_i'')$ and C_i, in the brown shrimp fishery of Texas, Louisiana, and adjoining EEZ, for the year 1981 (see Eqs. (2) and (4); Tables 2 and 3).

Table 2
Annual index b of the distribution of weight of landings among count categories, in the brown shrimp fishery of Texas, Louisiana, and adjoining Gulf of Mexico EEZ, 1960–2006

Year	b	ln(a)	r^2	F
1960	−0.0388	5.191	0.948	110.9
1961	−0.0369	5.173	0.958	136.7
1962	−0.0339	5.084	0.977	251.2
1963	−0.0314	5.029	0.951	116.4
1964	−0.0367	5.145	0.997	2035.0
1965	−0.0298	5.028	0.974	228.0
1966	−0.0311	5.026	0.959	141.6
1967	−0.0325	5.101	0.949	112.1
1968	−0.0274	5.019	0.963	157.2
1969	−0.0214	4.873	0.977	253.6
1970	−0.0279	4.970	0.971	205.2
1971	−0.0258	4.992	0.971	204.2
1972	−0.0311	5.088	0.980	287.8
1973	−0.0222	4.910	0.993	890.7
1974	−0.0264	4.956	0.955	127.4
1975	−0.0252	4.960	0.987	463.3
1976	−0.0207	4.883	0.973	220.0
1977	−0.0230	4.972	0.987	441.6
1978	−0.0177	4.879	0.997	2136.6
1979	−0.0180	4.864	0.997	2336.1
1980	−0.0209	4.899	0.985	407.0
1981	−0.0213	4.957	0.975	238.0
1982	−0.0159	4.818	0.977	257.1
1983	−0.0149	4.824	0.979	285.2
1984	−0.0188	4.889	0.980	288.8
1985	−0.0185	4.881	0.994	1075.2
1986	−0.0189	4.879	0.998	2451.3
1987	−0.0182	4.911	0.991	630.0
1988	−0.0221	4.983	0.987	449.5
1989	−0.0214	4.951	0.994	1008.5
1990	−0.0167	4.854	0.997	2002.1
1991	−0.0196	4.857	0.992	748.5
1992	−0.0185	4.885	0.990	622.3
1993	−0.0140	4.779	0.999	6367.6
1994	−0.0192	4.871	0.995	1205.6
1995	−0.0159	4.802	0.994	1034.3
1996	−0.0141	4.795	0.997	1872.8
1997	−0.0137	4.787	0.996	1363.1
1998	−0.0151	4.840	0.989	564.9
1999	−0.0133	4.769	0.996	1681.2
2000	−0.0178	4.883	0.996	1411.9
2001	−0.0184	4.920	0.971	199.4
2002	−0.0172	4.888	0.983	341.6
2003	−0.0148	4.843	0.989	523.7
2004	−0.0144	4.792	0.997	2257.6
2005	−0.0168	4.812	0.994	1045.4
2006	−0.0218	4.893	0.975	232.3

The intercept ln(a), adjusted coefficient of determination r^2, and ANOVA F are also shown for each linear regression (see Eq. (2)). All regressions were significant at $p < 0.001$.

Eq. (2) (Table 2), was very closely correlated with b. Adjusted $r^2 = 0.935$ for the regression of $\ln(a) = 4.596 - 14.95b$, based on the 47-year series.

2.2. Annual index d of the distribution of nominal ex-vessel value of landings among count categories

We calculated annual index d (Table 3) of the distribution of nominal ex-vessel value of landings among count categories in a manner similar to that used to calculate annual index b. Nominal ex-vessel value among count categories was not adjusted for inflation, under the assumption that within-year inflation is negligible as compared to year-to-year inflation. Annual summations of nominal ex-vessel value by count category over all trips in a year aggregated within-year inflation effects. The <15 count category was excluded in the estimation of d for the same reasons it was excluded from the estimation of b.

Table 3
Annual index d of the distribution of nominal ex-vessel value of landings among count categories, in the brown shrimp fishery of Texas, Louisiana, and adjoining Gulf of Mexico EEZ, 1960–2006

Year	d	ln(c)	r^2	F
1960	−0.0502	5.333	0.951	116.6
1961	−0.0497	5.351	0.952	120.9
1962	−0.0473	5.266	0.972	209.8
1963	−0.0505	5.281	0.949	113.7
1964	−0.0522	5.336	0.995	1135.7
1965	−0.0442	5.221	0.974	223.5
1966	−0.0491	5.316	0.971	202.1
1967	−0.0500	5.355	0.955	128.1
1968	−0.0473	5.300	0.960	145.0
1969	−0.0384	5.085	0.974	222.6
1970	−0.0462	5.187	0.961	148.9
1971	−0.0481	5.323	0.977	261.6
1972	−0.0507	5.382	0.977	258.1
1973	−0.0364	5.114	0.993	831.0
1974	−0.0466	5.156	0.939	92.8
1975	−0.0478	5.316	0.990	585.7
1976	−0.0411	5.149	0.972	209.8
1977	−0.0404	5.218	0.980	288.0
1978	−0.0376	5.169	0.996	1462.7
1979	−0.0326	5.058	0.994	975.7
1980	−0.0344	5.082	0.979	284.1
1981	−0.0377	5.195	0.984	360.1
1982	−0.0312	5.006	0.966	172.1
1983	−0.0271	4.992	0.973	218.6
1984	−0.0335	5.059	0.965	164.7
1985	−0.0356	5.069	0.993	855.6
1986	−0.0365	5.072	0.977	255.8
1987	−0.0243	4.847	0.975	230.5
1988	−0.0318	4.947	0.983	353.3
1989	−0.0309	4.984	0.981	316.8
1990	−0.0258	4.876	0.970	191.8
1991	−0.0297	4.896	0.966	171.7
1992	−0.0226	4.815	0.973	213.9
1993	−0.0231	4.777	0.953	122.4
1994	−0.0283	4.938	0.996	1637.2
1995	−0.0249	4.803	0.943	100.0
1996	−0.0233	4.794	0.973	215.1
1997	−0.0220	4.813	0.991	687.5
1998	−0.0237	4.849	0.981	308.8
1999	−0.0242	4.795	0.965	165.5
2000	−0.0246	4.899	0.992	793.5
2001	−0.0206	4.807	0.982	327.0
2002	−0.0206	4.802	0.991	690.4
2003	−0.0210	4.831	0.989	533.4
2004	−0.0248	4.757	0.941	97.3
2005	−0.0214	4.726	0.950	115.0
2006	−0.0319	4.947	0.970	191.8

The intercept ln(c), adjusted coefficient of determination r^2, and ANOVA F are also shown for each linear regression (see Eq. (4)). All regressions were significant at $p < 0.001$.

The exponential model underlying estimation of d is

$$P_i'' = c\,e^{dC_i} \quad (3)$$

where d is the annual index of the distribution of nominal ex-vessel value of landings among count categories; P_i'' is the annual cumulative percentage of nominal ex-vessel value of landings within the count category with ith lower limit; C_i is the ith lower limit (15, 21, 26, 31, 41, 51, and 68) of seven ($i = 1, 2, \ldots, 7$) of the eight standard count categories, respectively; c is an empirical constant, and e is the natural logarithm base.

A natural logarithmic transformation of Eq. (3) linearized it to

$$\ln(P_i'') = \ln(c) + dC_i \quad (4)$$

Examples of cumulative percentages P_i'' and the linear regression (Eq. (4)) in 1981 are shown in Fig. 2C and D, respectively. A right facing tick mark on the ordinate of Fig. 2D marks the data point for the <15 count category, which was included in the graph only for visual comparison with data points of the other count categories.

Like index b, slope d has only negative values (Table 3). An increase in d indicates a shift in the distribution of nominal ex-vessel of landings among count categories toward smaller shrimp, and a decrease in d indicates a shift toward larger shrimp. The empirical constant $\ln(c)$, estimated in fitting Eq. (4), was closely correlated with d. Adjusted $r^2 = 0.946$, for the regression $\ln(c) = 4.389 - 18.88d$, for the 47-year series.

2.3. Additional fishery-dependent variables

We calculated the difference, D, between each year's pair of annual indices b (Table 2) and d (Table 3), as $D = b - d$, so that D had only positive values. Both b and d are based on the annual distribution of weight of landings among count categories. However, d also incorporates differences in nominal ex-vessel value per pound among the count categories. Therefore, D is an index of differences in nominal ex-vessel value per pound among the seven count categories used in estimating b and d. An increase in D indicates a widening of differences in nominal ex-vessel value per pound among count categories, and a decrease in D indicates a narrowing.

Annual yield in weight of landings, W, was obtained by summing, over all trips and temporal–spatial cells in each year, the weight of count-graded landings plus landings in the "pieces" and "unknown" categories. Annual nominal ex-vessel value of landings was obtained by summing, over all trips and temporal–spatial cells in each year, the estimated nominal ex-vessel value of landings, including count-graded, "pieces", and "unknown". These annual totals for nominal ex-vessel value were converted to annual, inflation-adjusted ex-vessel value, V, in U.S.$ (2006), using the annual producer price index (PPI_T).[9] To make this conversion, we divided each year's annual nominal ex-vessel value by the fraction PPI_T/PPI_{2006}. Annual average inflation-adjusted ex-vessel value per pound of landings, VPP, was calculated as $VPP = V/W$.

The estimation of annual nominal fishing effort, E, included only that effort determined to have targeted brown shrimp, since shrimp species other than brown shrimp can be caught during shrimp fishing trips. We used the method described by Nance (1992) to select effort targeting brown shrimp from the available trip effort data. Kutkuhn (1962) and Gallaway et al. (2003) described the standard method used by NMFS to estimate nominal fishing effort within temporal–spatial cells (month × Shrimp Statistical Subarea × depth zone). E was the annual sum of the individual estimates for brown shrimp over all temporal–spatial cells in the fishery, and represented the best available effort data for the 1960–2006 time series. However, Kutkuhn (1962) stated that "high correspondence between curves of effort and yield generally reflects the techniques used to estimate the former from the latter", suggesting that estimates of annual effort may not be completely independent (statistically) of annual yield. Gallaway et al. (2003) developed a new logbook method for estimating fishing effort that may solve this problem for the future. We derived annual average weight of landings per unit nominal fishing effort as $WPUE = W/E$. We emphasize that variables b, d, D, W, V, and VPP are not affected by methods used by NMFS to estimate E, but the variable WPUE could be affected.

2.4. Examination of trends and relationships

Statistical applications including SAS®, Microsoft® Excel, and Analyse-it® were used to fit first through sixth order polynomial regressions to each data pair, in search for trends in the fishery-dependent variables (Table 1) and relationships between selected pairs of these variables. According to Sokal and Rohlf (2000), high correlations among independent variables (i.e., those on the abscissa) can lead to rounding errors when calculations are done by computer. Therefore, the independent variable in each regression was coded by subtracting its arithmetic mean from each of its values, to reduce correlations between odd and even powers to zero. The resulting coefficients differ from those obtained without such coding, except for the highest order coefficient for each regression. We examined ANOVA results for each regression, and plots of variances of residuals (deviations from regression) versus the highest polynomial order of each. For each data pair, we accepted as best fitting the lowest order polynomial regression that minimized the variance of residuals (deviations from regression), as judged from the plots of variances of residuals. An adjusted r^2, overall F, and p were reported for each best fitting regression model. When a curve gave the best fit to a trend or relationship, it was examined for local maxima and minima using a MathCad® program. Local maxima and minima and the level of the independent variable at which they occurred were also estimated.

3. Results and discussion

Each estimate of b and d differed significantly from zero (at $p < 0.001$), and the linear regressions from which they were

[9] U.S. Department of Labor, Bureau of Labor Statistics (http://data.bls.gov/cgi-bin/surveymost). These annual PPI data are expressed in U.S.$ (1982), but we converted them to U.S.$ (2006).

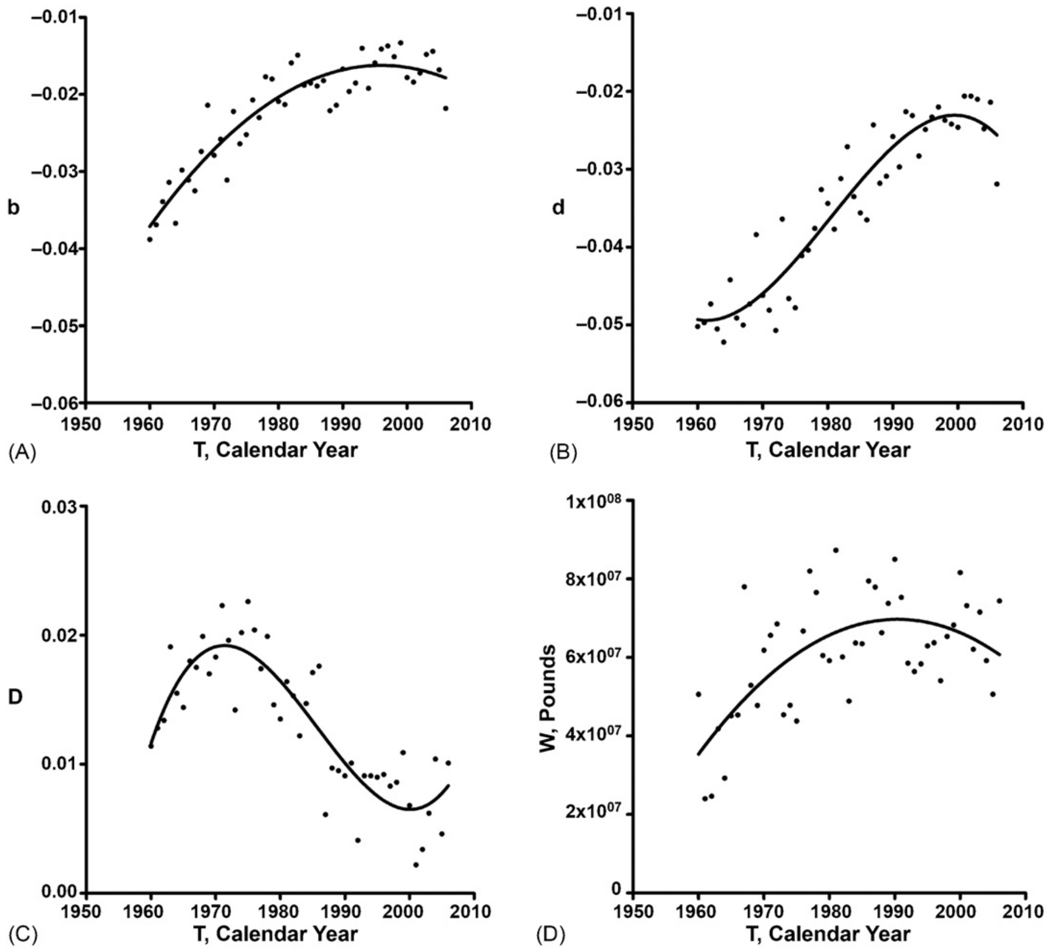

Fig. 3. Trends in b, d, D ($=b-d$) and W in the brown shrimp fishery of Texas, Louisiana, and adjoining Gulf of Mexico EEZ, during 1960–2006 (see Tables 1–5).

derived had high F and adjusted r^2, indicating very close fits of Eqs. (2) and (4) (Tables 2 and 3; Fig. 2B and D, respectively). Best fitting trends (Figs. 3 and 4) and relationships (Figs. 5 and 6) are shown with independent variables in their original scales (i.e., not coded).

Best fitting polynomial regressions fell into three groups with regard to goodness of fit, as indicated by adjusted r^2 (Table 4). The closest fitting (adjusted $r^2 > 0.8$) were b on T_{Coded}, d on T_{Coded}, and d on b_{Coded}. Intermediate in goodness of fit ($0.5 <$ adjusted $r^2 < 0.8$) were D on T_{Coded}, E on T_{Coded}, V on T_{Coded}, VPP on T_{Coded}, b on E_{Coded}, and V on E_{Coded}. Poorest fitting (adjusted $r^2 < 0.5$) were W on T_{Coded}, WPUE on T_{Coded}, W on b_{Coded}, V on b_{Coded}, and W on E_{Coded}. All but one of these polynomial regressions were significant at $p < 0.0001$ (Table 4). The exception was the regression of W on b_{Coded}, which was significant at $p = 0.0001$ (Table 4). Local maxima and minima within the data range for curved trends and relationships are shown in Table 5. Only the quadratic relationship between d on b_{Coded} had neither a maximum nor minimum within the data range (Table 5).

Polynomial regressions are empirical fits to data, and their polynomial terms have no structural meaning (Sokal and Rohlf, 2000). Therefore, caution should be exercised in interpreting our results. The best fitting trends and relationships reflected concomitant variation between pairs of variables, and did not necessarily represent cause and effect. Nevertheless, it is likely that causes and effects within this brown shrimp fishery influenced these regressions. We emphasize that significant trends and relationships were detected despite variability (deviations from regression) caused by environmentally influenced fluctuations in annual recruitment. Other factors could have contributed to the observed variability as well.

Trends in indices b and d (Fig. 3A and B, respectively), the trend in D (Fig. 3C), and the relationship between d on b (Fig. 5A), provided useful information not usually available in shrimp fishery assessments (Table 4). The trend in b (Fig. 3A) reached a maximum (−0.0162) in 1996 (Table 5), indicating decreasing size of shrimp before then and increasing size of shrimp thereafter. The trend in d (Fig. 3B) initially declined, reaching a minimum (−0.0494) in 1961, indicating that the distribution of nominal ex-vessel value of landings among count categories shifted briefly toward larger shrimp. Thereafter, d increased until it reached a maximum (−0.0230) in 1999, indicating a long duration shift toward smaller shrimp. Then, d declined again showing a shift toward larger shrimp. Because nominal ex-vessel value per pound characteristically increases with size of shrimp (Kutkuhn, 1962), b exceeded d in all years (Tables 2 and 3; Figs. 3A–C and 5A). In other words, slope d

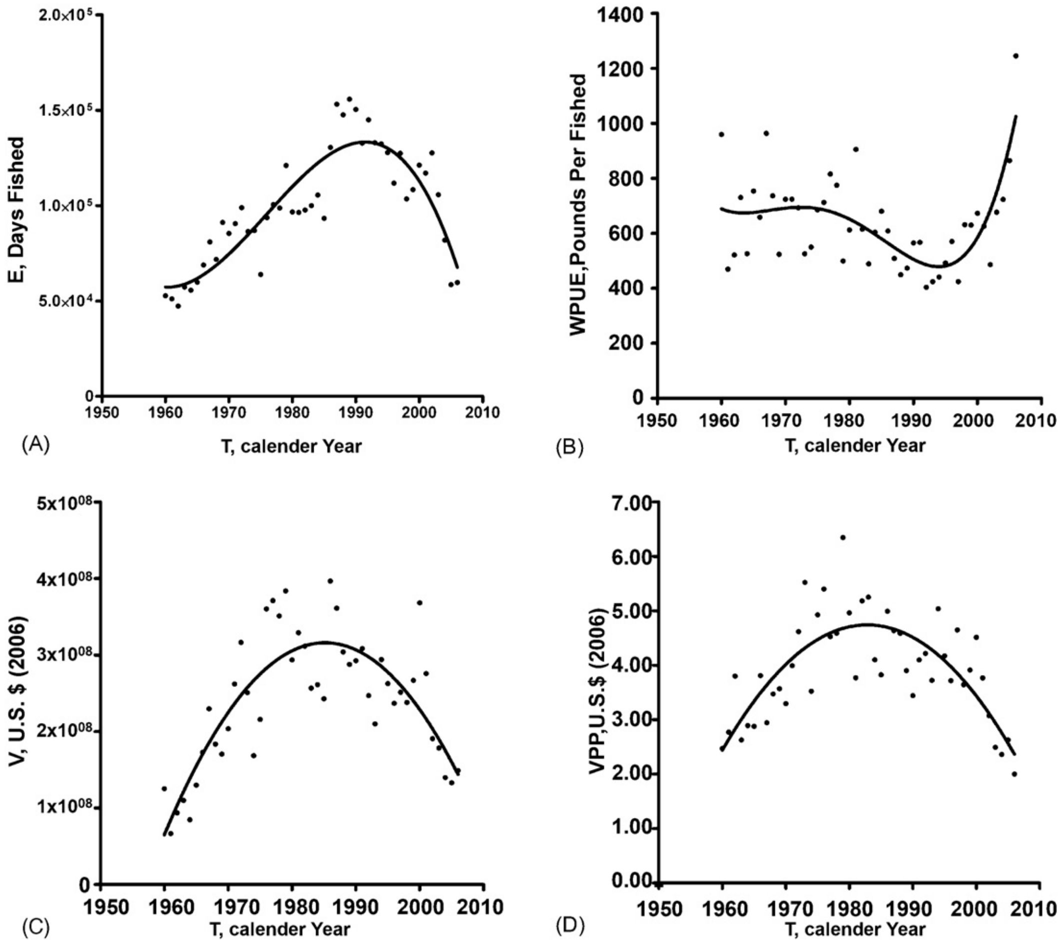

Fig. 4. Trends in E, WPUE, V, and VPP in the brown shrimp fishery of Texas, Louisiana, and adjoining Gulf of Mexico EEZ, during 1960–2006 (see Tables 1, 4 and 5).

(Eq. (4); Table 3) was steeper than slope b (Eq. (2); Table 2) in all years, showing that proportionately more of the nominal ex-vessel value of landings was concentrated in count categories containing larger shrimp than was the weight of landings (see examples, Fig. 2A–D). However, the difference D between b and d was not constant over the years. The trend in D was sigmoid, initially rising in the early years, reflecting a widening of the difference between b and d until D reached a maximum (0.0192) in 1971 (Tables 4 and 5; Fig. 3C). D then declined to reach its minimum (0.0065) in 2000. Theoretically, if D were to reach zero, the fitted straight lines (Eqs. (2) and (4), respectively) from which b and d are derived would be identical (i.e., superimposed). This could occur only if proportionate distributions of weight and nominal ex-vessel value of landings among count categories were identical, i.e., if there were no longer any differences in nominal ex-vessel value per pound among the count categories. Therefore, changes in D reflect changes in nominal ex-vessel value per pound (or price spread) among the count categories. At $D = 0$, nominal ex-vessel value per pound would no longer differ among the count categories. The trend in D, and the relationship between d and b, would be well worth monitoring in the future.

The trend in W showed an increase to its maximum of $6.97(10^7)$ pounds in 1990, declining thereafter (Tables 4 and 5; Fig. 3D). The trend in E showed a minimum of $5.72(10^4)$ days fished in 1960 and a maximum of $1.33(10^5)$ days fished in 1991, declining thereafter (Fig. 4A). The trend in WPUE (Fig. 4B) had two minima, one of 664 pounds in 1965 and a lower one of 469 pounds in 1994, thereafter showing a very sharp rise, which indicated that relative abundance improved remarkably with the decline in E. Year 2006 had the highest WPUE on record. This trend in WPUE is consistent with the concave upward trend in brown shrimp biomass (with a minimum in the early 1990s) measured by a fishery-independent trawling survey[2] conducted by NMFS in the northern Gulf of Mexico.

The trend in V reached its maximum, $3.16(10^8)$ U.S.$ (2006), in 1985 (Fig. 4C; Table 5), 2 years after the maximum in VPP, 4.74 U.S.$ (2006), occurred (Fig. 4D; Table 5). Both of these maxima preceded those for trends in b (1996), d (1999), W (1990) and E (1991), as well as the lowest of the two minima for the trend in WPUE (1994) (Table 5). However, they lagged well behind the maximum for the trend in D (Table 5). This suggests that effects of fishing, including its reduction in size of shrimp in the landings, were having major effects on V and VPP before the trend in W reached its maximum.

The relationship between W and b (Tables 4 and 5; Fig. 5B) was consistent with concepts of surplus production. It showed that W increased with the shift toward smaller sizes of shrimp

Table 4
Best fitting polynomial regressions for trends (over calendar years, T) in fishery-dependent variables (see Table 1 and for relationships between selected pairs of fishery-dependent variables, in the brown shrimp fishery of Texas, Louisiana, and adjoining Gulf of Mexico EEZ, 1960–2006

Regression[a]	Polynomial term	Coefficient[a]	r^2	F	p
b on T_{Coded}			0.848	128.91	<0.0001
	Intercept	$-1.8944912(10^{-2})$			
	Linear	$4.1934551(10^{-4})$			
	Quadratic	$1.6152765(10^{-5})$			
d on T_{Coded}			0.879	112.78	<0.0001
	Intercept	$-3.3583384(10^{-2})$			
	Linear	$1.0181426(10^{-3})$			
	Quadratic	$-7.3405357(10^{-6})$			
	Cubic	$-9.5112951(10^{-7})$			
D on T_{Coded}			0.754	48.01	<0.0001
	Intercept	$1.4638472(10^{-2})$			
	Linear	$-6.3941687(10^{-4})$			
	Quadratic	$-8.8122298(10^{-6})$			
	Cubic	$1.0738480(10^{-6})$			
W on T_{Coded}			0.401	11.25	<0.0001
	Intercept	$6.7648913(10^{7})$			
	Linear	$5.5131419(10^{5})$			
	Quadratic	$-3.7099339(10^{4})$			
E on T_{Coded}			0.769	52.00	<0.0001
	Intercept	$1.1949307(10^{5})$			
	Linear	$2.9073799(10^{3})$			
	Quadratic	$-1.0783605(10^{2})$			
	Cubic	-5.0712102			
WPUE on T_{Coded}			0.434	9.82	<0.0001
	Intercept	$6.2498005(10^{2})$			
	Linear	$-1.4891357(10^{1})$			
	Quadratic	$-6.5118504(10^{-1})$			
	Cubic	$4.1961314(10^{-2})$			
	Quartic	$2.1637771(10^{-3})$			
V on T_{Coded}			0.653	44.35	<0.0001
	Intercept	$3.1412865(10^{8})$			
	Linear	$1.7185854(10^{6})$			
	Quadratic	$-3.9644758(10^{5})$			
VPP on T			0.574	32.05	<0.0001
	Intercept	4.7409310			
	Linear	$-1.5933164(10^{-3})$			
	Quadratic	$-4.4182187(10^{-3})$			
d on b_{Coded}			0.832	114.65	<0.0001
	Intercept	$1.9485828(10^{-2})$			
	Linear	3.5203797			
	Quadratic	$4.3184313(10^{1})$			
W on b_{Coded}			0.310	11.34	0.0001
	Intercept	$3.3167206(10^{7})$			
	Linear	$-3.4723672(10^{9})$			
	Quadratic	$-9.2020681(10^{10})$			
V on b_{Coded}			0.359	13.89	<0.0001
	Intercept	$3.5292248(10^{6})$			
	Linear	$-2.6847097(10^{10})$			
	Quadratic	$-6.6620706(10^{11})$			
b on E_{Coded}			0.557	29.92	<0.0001
	Intercept	$-6.2321081(10^{-2})$			
	Linear	$7.0532186(10^{-7})$			
	Quadratic	$-2.7639195(10^{-12})$			

Table 4 (*Continued*)

Regression[a]	Polynomial term	Coefficient[a]	r^2	F	p
W on E_{Coded}			0.440	19.08	<0.0001
	Intercept	$-1.1762942(10^7)$			
	Linear	$1.2225395(10^3)$			
	Quadratic	$-4.5545910(10^{-3})$			
V on E_{Coded}			0.584	33.32	<0.0001
	Intercept	$-2.4564451(10^8)$			
	Linear	$8.3005061(10^3)$			
	Quadratic	$-3.1478394(10^{-2})$			

The adjusted coefficient of determination r^2, ANOVA F, and probability p are also shown for each regression.

[a] The independent variable was coded by subtracting its arithmetic mean from each of its values. However, trends and relationships in Figs. 3–6 are plotted in the original scale of each independent variable. Mean $T = 1983$, mean $b = -0.0219$, and mean $E = 99{,}651$ days fished.

in the landings, reached a maximum of $6.59(10^7)$ pounds at $b = -0.0189$, then declined as shrimp size continued to decrease (Table 5). Such a relationship is evidence of growth overfishing. In addition, the level of b at which maximum W occurs can be considered an optimum, reflecting the distribution of weight of landings among count categories at which W is maximized. The maximum for the trend in b (-0.0162) was higher than the level of b associated with maximum W, indicating that sizes of shrimp associated with the former were smaller than those associated with the latter.

The relationship between V and b (Tables 4 and 5; Fig. 5C) had a maximum of $2.74(10^8)$ U.S.$ (2006) at $b = -0.0202$, showing that V was maximized at a size distribution of shrimp reflecting larger sizes than those at which W was maximized. The level of b at which maximum V occurs can also be viewed as an optimum, reflecting the distribution of nominal ex-vessel value of landings among count categories at which V is maximized. Maxima V was $3.16(10^8)$ U.S.$ (2006) for the trend in V, $3.02(10^8)$ U.S.$ (2006) for the relationship between V and E, and $2.74(10^8)$ U.S.$ (2006) for the relationship between V and b.

The relationship between b and E (Tables 4 and 5; Fig. 6A) suggests that size of shrimp in the landings decreased as nominal fishing effort increased to a point, but b showed an unexpected decline (i.e., an increase in size of shrimp) at levels of E higher than $1.25(10^5)$ days fished at which b had a maximum (-0.0173). An asymptotic regression could have been fitted to describe this relationship, but we did not do so for consistency with our use of polynomial regression, and because there was an obvious downturn in b as levels of E continued to increase. Partial statistical dependence between E and W (Kutkuhn, 1962; Gallaway et al., 2003) may be a reason for this downturn in b.

The relationship between W on E had a maximum of $7.03(10^7)$ pounds at an E of $1.34(10^5)$ days fished (Tables 4 and 5; Fig. 6B). This maximum W is an estimate of MSY. This relationship was not forced through the origin ($W = 0$, $E = 0$), as it is in the Graham–Schaefer surplus production model which assumes the origin, and therefore it fits the data better. The relationship between W and E, with its maximum ($\approx$ MSY), suggests growth overfishing, given the caveat concerning the method used to estimate E. The maximum W associated with E, $7.03(10^7)$ pounds, was higher than the maximum for the trend in W, $6.97(10^7)$ pounds, which in turn was higher than the maximum W associated with b, $6.57(10^7)$ pounds, but these maxima did not differ greatly from each other.

The maximum V of $3.02(10^8)$ U.S.$ (2006) occurred at an E level of $1.32(10^5)$ days fished (Tables 4 and 5; Fig. 6C), which

Table 5

Trends and relationships that had estimable local maxima, minima, or both, and the estimated level of the independent variable at which each occurred, in the brown shrimp fishery of Texas, Louisiana, and adjoining Gulf of Mexico EEZ, 1960–2006 (see Tables 1 and 4)

Dependent variable	Local maxima	Independent variable	Local minima	Independent variable
b	-0.0162	$T = 1996$		
d	-0.0230	$T = 1999$	-0.0494	$T = 1961$
D	0.0192	$T = 1971$	0.0065	$T = 2000$
W	$6.97(10^7)$ pounds	$T = 1990$		
E	$1.33(10^5)$ days fished	$T = 1991$	$5.72(10^4)$ days fished	$T = 1960$
WPUE	$6.90(10^2)$ pounds	$T = 1974$	$6.64(10^2)$ pounds	$T = 1965$
			$4.69(10^2)$ pounds	$T = 1994$
V	$3.16(10^8)$ U.S.$ (2006)	$T = 1985$		
VPP	4.74 U.S.$ (2006)	$T = 1983$		
W	$6.59(10^7)$ pounds	$b = -0.0189$		
V	$2.74(10^8)$ U.S.$ (2006)	$b = -0.0202$		
b	-0.0173	$E = 1.25(10^5)$ days fished		
W	$7.03(10^7)$ pounds $\approx$ MSY	$E = 1.34(10^5)$ days fished		
V	$3.02(10^8)$ U.S.$ (2006)	$E = 1.32(10^5)$ days fished		

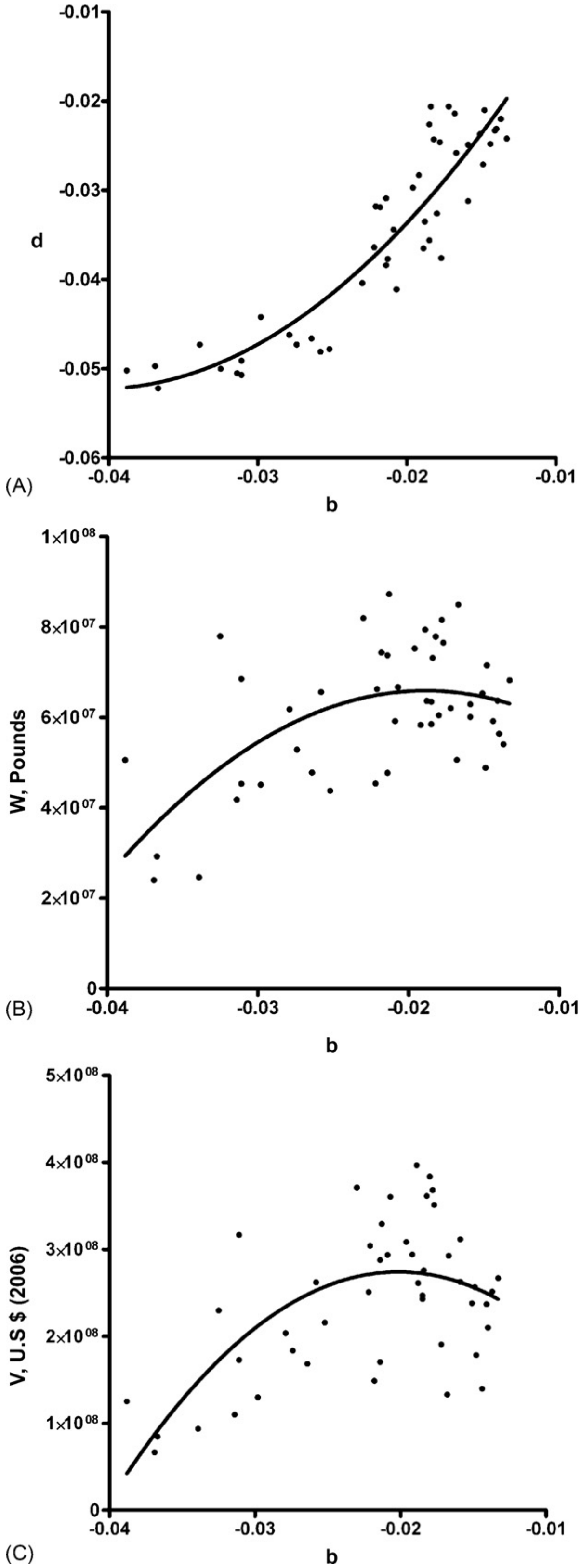

Fig. 5. Relationships between d and b, W and b, and V and b, in the brown shrimp fishery of Texas, Louisiana, and adjoining Gulf of Mexico EEZ, during 1960–2006 (see Tables 1–5).

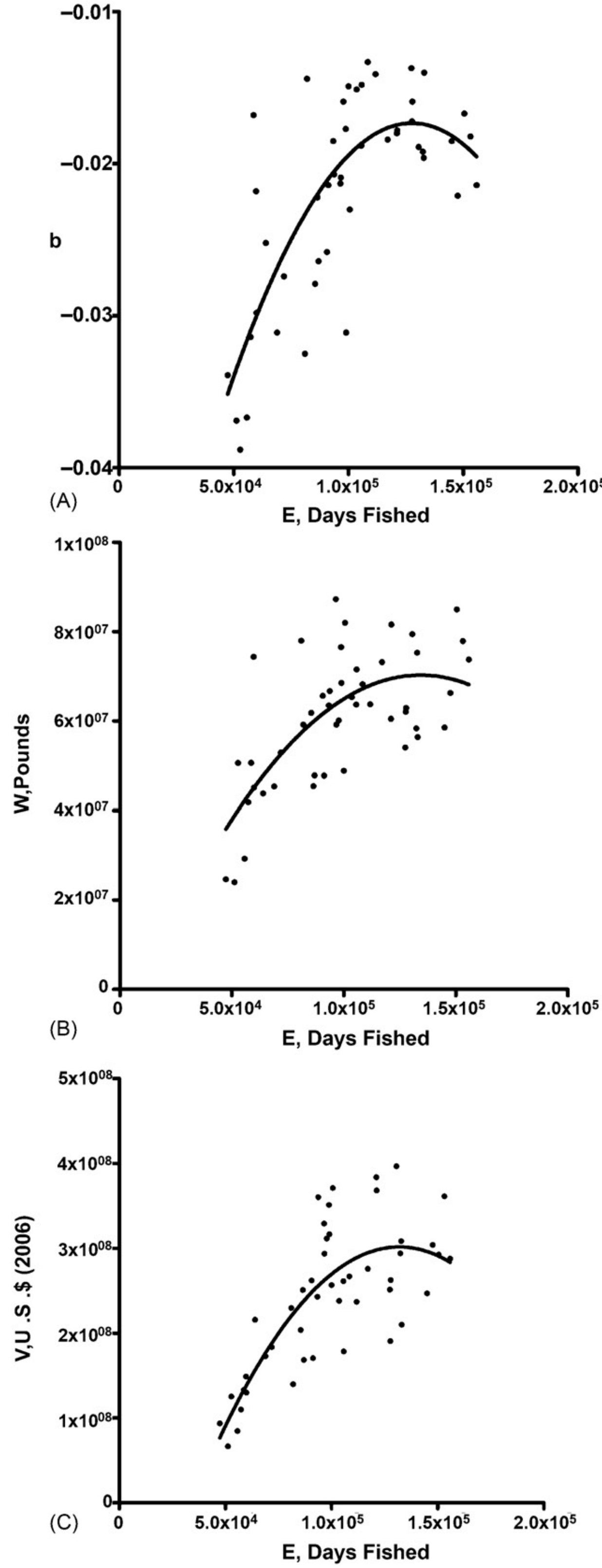

Fig. 6. Relationships between b and E, W and E, and V and E, in the brown shrimp fishery of Texas, Louisiana, and adjoining Gulf of Mexico EEZ, during 1960–2006 (see Tables 1, 2, 4 and 5).

was lower than that at which *W* was maximized in relation to *E*. This suggests that economic effects of fishing brought about by decreases of size of shrimp in the landings were evident prior to the occurrence of growth overfishing.

4. Unevaluated influences

Commercial shrimpers' long-standing practice of discarding small shrimp to increase ex-vessel value of their landings (Kutkuhn, 1962) would be a problem for our analyses only if a significant trend of change in discarding rate occurred over the time series. Small shrimp are sometimes discarded to increase size of shrimp landed, as related to marketing. Rothschild and Brunenmeister (1984) mentioned seasonal changes in brown shrimp discarding rates, which peaked early in the shrimping season. They said that discarding rates were high at times, and variable among years, but they did not mention whether there was a significant trend in discarding rate over years. Available data on discarding were too limited and variable to determine their potential effects on the annual distribution of size of shrimp in the landings. We assumed the effects of discarding on our results were negligible, and we found no evidence to the contrary over the time series.

Significant trends of change in traveling distance to and from fishing grounds, duration of fishing trips, market demand for shrimp of various sizes, operating costs, characteristics of shrimp fishing units and gear, and other factors could also have influenced our results. Again, we have no evidence of such trends over the time series.

5. Conclusions

Were it not for exogenous economic factors such as rising fuel costs and competition from imported shrimp,[2–6] which led to the decline in *E* following the early 1990s, continued growth overfishing might have put this brown shrimp fishery at risk of recruitment overfishing (Rothschild and Brunenmeister, 1984). Growth overfishing occurred but abated with this decline in *E*. Fleet size also declined[5], and was further reduced by catastrophic impacts of hurricanes[2] in the northern Gulf in 2005. Years before, the effects of increased fishing effort and decline in size of shrimp in the landings were evident in the form of declines in inflation-adjusted ex-vessel value of the landings and inflation-adjusted ex-vessel value per pound. The brown shrimp stock appears to be recovering[2] (Fig. 4B) from growth overfishing.

Warnings by Rothschild and Brunenmeister (1984) apparently went unheeded, and detrimental socio-economic consequences of further increases in fishing effort occurred before rising fuel costs, competition from imported shrimp, and other exogenous factors caused fishing effort and fleet size to decline. The fleet size moratorium should limit future expansion of the fleet that fishes the EEZ. The new shrimping regulations implemented by the TPWD in 2001 should also limit expansion of the fleet that fishes Texas' waters. In our opinion, these management actions were in the right direction. Nevertheless, the effects of fishing effort on size of shrimp in the landings, the potential for growth overfishing, and associated detrimental economic effects should be included among guidelines for future management of this fishery by Federal and State agencies.

Our investigation suggests that past management strategies encouraging the harvest of all the shrimp possible from each annual crop (with relatively few constraints) led to growth overfishing in this brown shrimp fishery. Larger shrimp generally have higher ex-vessel values per pound than do smaller shrimp, but the differences in ex-vessel value per pound among count categories have narrowed. It is clear that sizes of shrimp landed, yields of shrimp, and inflation-adjusted ex-vessel value of these yields are inextricably intertwined (Nance et al., 1994). There remains a need for further economic studies that evaluate effects of size of shrimp landed on MSY and OY. There probably exists in any given year an economically optimum shrimp size related to the level of fishing effort, the ex-vessel value per pound of shrimp of various sizes, and the costs of fishing. Costs of fishing are variable, and optimum shrimp size cannot be determined until fishery information for a given year has been evaluated. However, observed trends in fishery-dependent variables, including those for *b*, *d*, and *D*, can be useful in predicting optimum shrimp size, as a guide to management. Our paper was not intended as an economic assessment of this brown shrimp fishery, but it provides information of possible use to future economic assessments. It remains to be determined whether the observed declines in fishing effort and fleet size will increase profitability in this brown shrimp fishery, or in the domestic shrimp fishery of the Gulf of Mexico as a whole.

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